UM–SJTU JOINT INSTITUTE
PHYSICS LABORATORY
(VP241)

LABORATORY REPORT

EXERCISE 3

SOLAR CELLS: I-V CHRACTERISTICS

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1 Introduction

The objective of this exercise is to urge students to be familiar with the working principle of a solar cell and study its current-voltage *(I-V)* characteristics.

1.1 Basic Concepts

- **Solar cell:**[1] Solar cells are devices which are able to directly transform solar radiation into electrical energy.

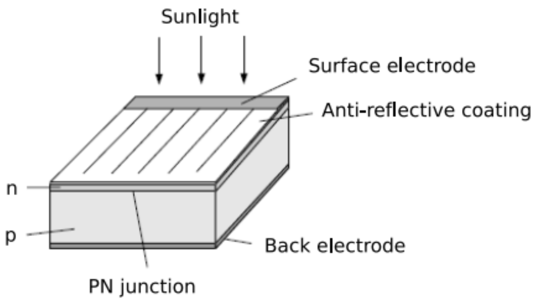

Figure 1: Solar cell

- **P-N junction:**[2] A p–n junction is a boundary or interface between two types of semiconductor materials, p-type and n-type, inside a single crystal of semiconductor.

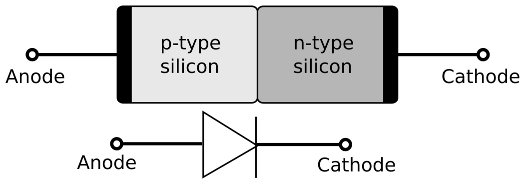

Figure 2: P-N junction

- **Photovoltaic (PV) effect:**[3] Photovoltaic (PV) effect is a process by which PV cell converts the absorbed sunlight energy into electricity.

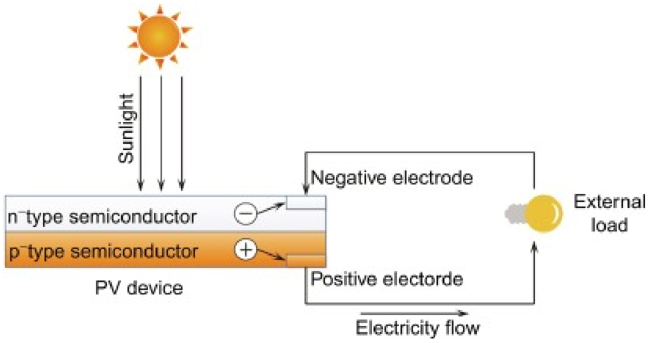

Figure 3: Photovoltaic effect

- **Fill factor:** Fill factor is the available power at the maximum power point (P_{m}) divided by the open circuit voltage (V_{OC}) and the short circuit current (I_{sc}).

$$FF = \frac{P_{\mathrm{m}}}{V_{\mathrm{oc}} I_{\mathrm{sc}}} = \frac{V_{\mathrm{m}} I_{\mathrm{m}}}{V_{\mathrm{oc}} I_{\mathrm{sc}}} \tag{1}$$

- **Solar cell energy conversion efficiency:** The solar cell energy conversion efficiency η is defined as

$$\eta = \frac{P_{\mathrm{m}}}{P_{\mathrm{in}}} \times 100\% \tag{2}$$

where P_{in} denotes the total radiant power incident on the solar cell while P_{m} denotes the maximum output power.

1.2 Theoretical Basis

1.2.1 The Principle of the Photovoltaic Effect[1]

When the light enters the $p-n$ junction near the solar cell surface, and the energy of incident photons is greater than the forbidden bandwidth (energy gap) E_g, the incident photons are absorbed and excite electron-hole pairs. Minority charge carriers in the $n-$ or $p-$type area diffuse due to their density gradient. Some of them are able to diffuse to the region of the $p-n$ junction where a built-in electric field exists. This field is directed from the $n-$type to the $p-$type area. The minority carriers diffusing to the $p-n$ junction zone between the $n-$type area and the $p-$type area are drawn by this electric field to the $p-$type area (in case of the holes), or to the n-type area (in case of the electrons). This results in an increase of positive charge accumulated in the p-type area and negative charge in the $n-$type area. Consequently, a photoelectric potential difference is generated.

1.2.2 Solar Cell Parameters

The net current I is

$$I = I_{\mathrm{ph}} - I_{\mathrm{D}} = I_{\mathrm{ph}} - I_0 \left[\exp\left(\frac{qV_{\mathrm{D}}}{nk_{\mathrm{B}}T}\right) - 1\right] \tag{3}$$

where I_{ph} is the current from the $n-$type area to the $p-$area when there is light incident on the solar cell and I_D is a forward diode current from the $p-$type to the $n-$type area, opposite to I_{ph}. V_D is the junction voltage, I_0 is the diode inverse saturation current, the coefficient n is a theoretical coefficient, with its values ranging from 1 to 2, that characterizes the $p-n$ junction. Furthermore, q denotes the electron's charge, k_B is the Boltzmann's constant, and T is the temperature in the absolute (Kelvin) scale.

Ignoring the internal series resistance R_s, the voltage V_D equals the terminal voltage V and Eq.(3) can be rewritten as

$$I = I_{\mathrm{ph}} - I_0 \left[\exp\left(\frac{qV}{nk_{\mathrm{B}}T}\right) - 1\right] \tag{4}$$

When the output is short, *i.e.*, $V=0$, the short-circuit current is

$$I_{\mathrm{sc}} = I_{\mathrm{ph}}$$

whereas when the output is open, *i.e.*, $I=0$, the open-circuit voltage is

$$V_{\mathrm{oc}} = \frac{nk_{\mathrm{B}}T}{q} \ln\left(\frac{I_{\mathrm{sc}}}{I_0} + 1\right) \tag{5}$$

1.2.3 Theoretical Graph

Considering Eq.(4) and Eq.(5), the corresponding $I-V$ characteristics curve is shown in Fig.(4)

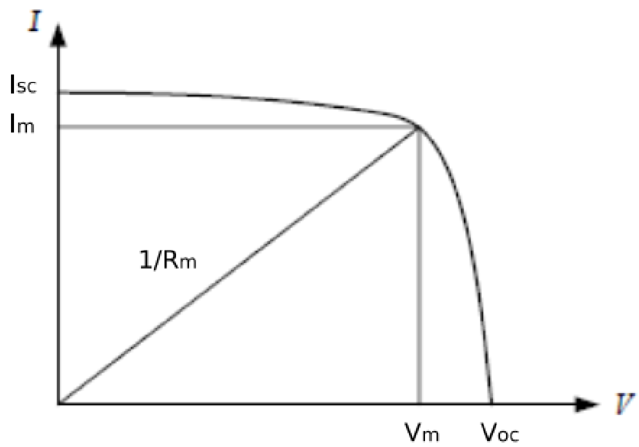

Figure 4: The current-voltage characteristics of a solar cell.

1.2.4 Solar Cell Equivalent Circuit

As shown in Fig.(5) , a solar cell can be thought of as composed of a $p-n$ junction diode D and a constant current source I_{ph}. Along with a series resistance R_{s} due to the electrodes in the solar cell and a parallel resistance R_{sh}, all elements form a circuit equivalent to a p - n junction leak-circuit. For the equivalent circuit one can find the following relationship between the current and the voltage

$$I = I_{\mathrm{ph}} - I_0 \left\{ \exp\left[\frac{q\,(V + R_{\mathrm{s}}I)}{nk_{\mathrm{B}}T} \right] - 1 \right\} - \frac{V + R_{\mathrm{s}}I}{R_{\mathrm{sh}}}$$

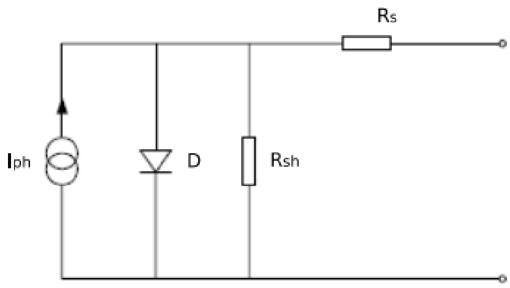

Figure 5: Solar cell equivalent circuit.

2 Apparatus and Measurement Procedure

2.1 Apparatus

The setup consists of a photovoltaic device (5 W), a 300 W tungsten-halogen lamp serving as a radiation source, two digital multimeters, two adjustable resistors, a solar power meter, a wiring board and a measuring tape.

The precisions of the devices are shown in Table 1.

Instrument	Uncertainties
DC Voltage	$\pm(0.5\% + 0.01)\,\mathrm{V}$
DC Current	$\pm(1.5\% + 0.1\,\mathrm{mA}$
Distance	$\pm 0.1\%\,\mathrm{cm}$
Solar power	$\pm 10\,\mathrm{W/cm^2}$

Table 1: Information of measurement instruments.

2.2 Measurement Procedure

In this exercise, the characteristics of four configurations of the solar cell are studied. For each configuration, the $I - V$ $P - V$, $P - R$ relations are studied and for each single configurations, the information about fill factor and energy conversion efficiency are also explored.

1. Turn on both the light and the fan and then wait until the light reaches its working intensity.
2. Design a measuring circuit with the photovoltaic device, multimeters set in an appropriate range, and the resistance. Connect the elements into a circuit using the provided wiring board.
3. Adjust the distance between the light source and the photovoltaic device until the V_{oc} and I_{sc} of the two devices are about the same. Measure the solar power by the provided solar power meter.
4. Change the distance between the light source and the photovoltaic device and measure the $I - V$ characteristics curves and the values of V_{oc} and I_{sc} in a single-device configuration. Measure the solar power at this distance.
5. Plot

2.3 Safety Notice

- The temperature of the light source is very high, do not touch the cover.
- The power supply voltage of the light source is 220 V, beware of electric shock.

3 Experimental Results

First, we need to clarify the area we measured since the energy provided is closely related to the area of solar cells. Corresponding data is as follows.

length [cm]	width [cm]
21.00	26.10

Table 2: Measurement data for area

3.1 $I - V$ Characteristics

The measurement data for U and I under different conditions are shown in Table 3.

	Series		Parallel	
	$U \pm (0.5\% + 0.01)$ [V]	$I \pm (1.5\% + 0.1)$ [mA]	$U \pm (0.5\% + 0.01)$ [V]	$I \pm (1.5\% + 0.1)$ [mA]
1	1.89 ± 0.02	43.5 ± 0.8	0.61 ± 0.013	90.5 ± 1.5
2	2.67 ± 0.03	43.2 ± 0.8	1.17 ± 0.016	88.0 ± 1.5
3	3.45 ± 0.03	42.1 ± 0.8	1.45 ± 0.018	87.0 ± 1.4
4	4.82 ± 0.04	40.7 ± 0.8	1.71 ± 0.019	85.6 ± 1.4
5	6.77 ± 0.05	39.3 ± 0.7	2.14 ± 0.02	83.8 ± 1.4
6	7.55 ± 0.05	38.4 ± 0.7	2.43 ± 0.03	82.4 ± 1.4
7	8.44 ± 0.06	37.1 ± 0.7	2.97 ± 0.03	79.7 ± 1.3
8	8.82 ± 0.06	35.6 ± 0.7	3.28 ± 0.03	78.2 ± 1.3
9	9.60 ± 0.06	34.3 ± 0.7	3.56 ± 0.03	76.5 ± 1.3
10	10.53 ± 0.07	32.0 ± 0.6	4.02 ± 0.03	73.9 ± 1.2
11	3.09 ± 0.03	43.0 ± 0.8	4.40 ± 0.03	71.3 ± 1.2
12	4.08 ± 0.03	42.0 ± 0.8	4.83 ± 0.04	67.7 ± 1.2
13	5.53 ± 0.04	40.5 ± 0.7	5.15 ± 0.04	64.4 ± 1.1
14	9.16 ± 0.06	35.4 ± 0.7	5.45 ± 0.04	61.2 ± 1.0
15	11.44 ± 0.07	28.6 ± 0.6	5.76 ± 0.04	57.6 ± 1.0
16	11.15 ± 0.07	29.5 ± 0.6	6.09 ± 0.04	53.3 ± 0.9
17	11.54 ± 0.07	28.9 ± 0.6	6.44 ± 0.05	47.9 ± 0.9
18	12.00 ± 0.07	26.7 ± 0.5	6.75 ± 0.05	42.4 ± 0.8
19	12.71 ± 0.08	24.2 ± 0.5	6.92 ± 0.05	38.8 ± 0.7
20	13.13 ± 0.08	22.4 ± 0.5	7.38 ± 0.05	27.8 ± 0.6
21	13.51 ± 0.08	20.7 ± 0.5	7.15 ± 0.06	33.4 ± 0.6
22	13.97 ± 0.08	18.3 ± 0.4	7.53 ± 0.05	23.5 ± 0.5
23	14.35 ± 0.09	16.2 ± 0.4	7.68 ± 0.05	19.1 ± 0.4
24	14.43 ± 0.09	15.6 ± 0.4	7.85 ± 0.05	13.9 ± 0.3
25	14.61 ± 0.09	14.6 ± 0.4	7.98 ± 0.05	9.3 ± 0.3

Table 3: Measurement data for the U vs. I relation (series/parallel configuration).

	100 cm		144 cm	
	$U \pm (0.5\% + 0.01)$ [V]	$I \pm (1.5\% + 0.1)$ [mA]	$U \pm (0.5\% + 0.01)$ [V]	$I \pm (1.5\% + 0.1)$ [mA]
1	9.15 ± 0.06	9.3 ± 0.2	0.47 ± 0.012	36.9 ± 0.7
2	9.09 ± 0.06	11.1 ± 0.3	0.89 ± 0.014	36.4 ± 0.6
3	9.00 ± 0.06	13.8 ± 0.3	1.39 ± 0.017	35.8 ± 0.6
4	8.94 ± 0.05	15.7 ± 0.3	1.81 ± 0.019	35.1 ± 0.6
5	8.86 ± 0.05	17.9 ± 0.4	2.16 ± 0.02	34.5 ± 0.6
6	8.80 ± 0.05	19.7 ± 0.4	2.92 ± 0.02	33.0 ± 0.6
7	8.65 ± 0.05	23.5 ± 0.5	3.38 ± 0.03	32.3 ± 0.6
8	8.46 ± 0.05	27.5 ± 0.5	3.71 ± 0.03	31.6 ± 0.6
9	8.33 ± 0.05	30.1 ± 0.6	4.21 ± 0.03	30.7 ± 0.6
10	8.21 ± 0.05	32.2 ± 0.6	4.63 ± 0.03	29.8 ± 0.5
11	8.07 ± 0.05	34.4 ± 0.6	5.01 ± 0.04	29.1 ± 0.5
12	7.92 ± 0.05	36.5 ± 0.6	5.44 ± 0.04	28.2 ± 0.5
13	7.75 ± 0.05	38.8 ± 0.7	5.75 ± 0.04	27.0 ± 0.5
14	7.59 ± 0.05	40.5 ± 0.7	6.09 ± 0.04	25.2 ± 0.5
15	7.37 ± 0.05	42.6 ± 0.7	6.46 ± 0.04	23.0 ± 0.4
16	6.71 ± 0.04	48.2 ± 0.8	6.71 ± 0.04	21.1 ± 0.4
17	6.22 ± 0.04	50.7 ± 0.9	6.96 ± 0.04	19.1 ± 0.4
18	5.52 ± 0.04	53.7 ± 0.9	7.08 ± 0.05	18.0 ± 0.4
19	5.21 ± 0.04	54.8 ± 0.9	7.24 ± 0.05	16.4 ± 0.3
20	4.77 ± 0.03	56.1 ± 0.9	7.38 ± 0.05	14.9 ± 0.3
21	4.58 ± 0.03	57.1 ± 1.0	7.51 ± 0.05	13.6 ± 0.3
22	3.61 ± 0.03	60.7 ± 1.0	7.68 ± 0.05	11.6 ± 0.3
23	2.97 ± 0.02	62.2 ± 1.0	7.72 ± 0.05	11.0 ± 0.3
24	1.69 ± 0.018	64.7 ± 1.1	7.80 ± 0.05	9.8 ± 0.2
25	1.04 ± 0.015	66.0 ± 1.1	7.90 ± 0.05	8.6 ± 0.2

Table 4: Measurement data for the U vs. I relation (100 cm/144 cm configuration).

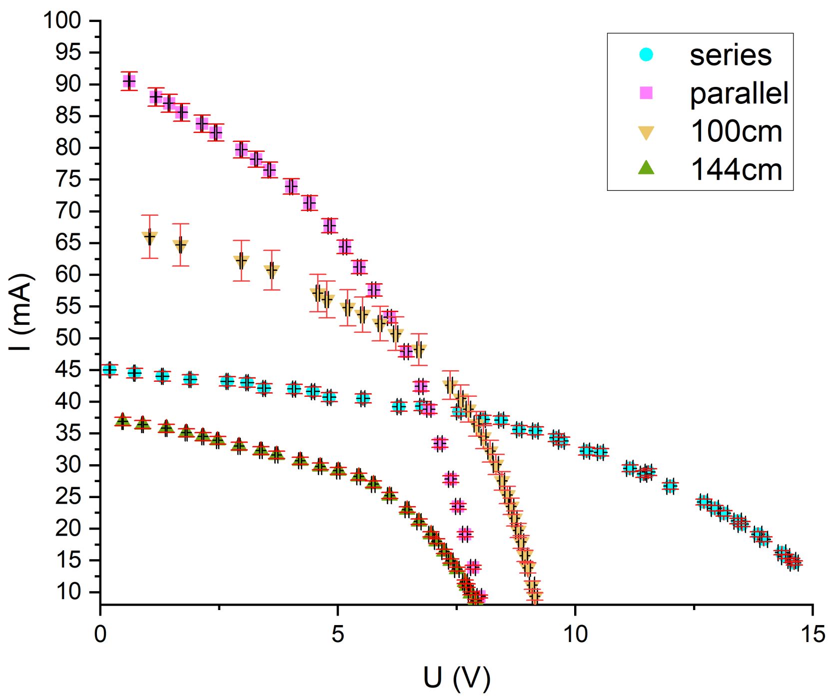

Figure 6: $I - V$ characteristic curves of each configuration.

3.2 $P - V$ Characteristics

Here we try to plot the characteristics graph of $P - V$ relation.

The power of the solar cell is calculated as the product of V and I. Take the first set of data as an example,

$$P = VI = 1.89 \times 43.5 \times 10^{-3} = 0.082 \pm 0.002 \text{ W}.$$

Perform simialr calculation for each set of data, the results are presented in Table 5 and Table 6.

	Series		Parallel	
	$U \pm (0.5\% + 0.01)$ [V]	P [W]	$U \pm (0.5\% + 0.01)$ [V]	P [W]
1	1.89 ± 0.02	0.082 ± 0.002	0.61 ± 0.013	0.0552 ± 0.0015
2	2.67 ± 0.03	0.115 ± 0.002	1.17 ± 0.016	0.103 ± 0.002
3	3.45 ± 0.03	0.145 ± 0.003	1.45 ± 0.018	0.126 ± 0.003
4	4.82 ± 0.04	0.196 ± 0.004	1.71 ± 0.019	0.146 ± 0.003
5	6.77 ± 0.05	0.266 ± 0.005	2.14 ± 0.02	0.179 ± 0.003
6	7.55 ± 0.05	0.290 ± 0.005	2.43 ± 0.03	0.200 ± 0.004
7	8.44 ± 0.06	0.313 ± 0.006	2.97 ± 0.03	0.237 ± 0.004
8	8.82 ± 0.06	0.314 ± 0.006	3.28 ± 0.03	0.256 ± 0.005
9	9.60 ± 0.06	0.329 ± 0.006	3.56 ± 0.03	0.272 ± 0.005
10	10.53 ± 0.07	0.337 ± 0.006	4.02 ± 0.03	0.297 ± 0.005
11	3.09 ± 0.03	0.133 ± 0.003	4.40 ± 0.03	0.314 ± 0.006
12	4.08 ± 0.03	0.171 ± 0.003	4.83 ± 0.04	0.327 ± 0.006
13	5.53 ± 0.04	0.224 ± 0.004	5.15 ± 0.04	0.332 ± 0.006
14	9.16 ± 0.06	0.324 ± 0.006	5.45 ± 0.04	0.334 ± 0.006
15	11.44 ± 0.07	0.327 ± 0.006	5.76 ± 0.04	0.332 ± 0.006
16	11.15 ± 0.07	0.329 ± 0.006	6.09 ± 0.04	0.325 ± 0.006
17	11.54 ± 0.07	0.334 ± 0.006	6.44 ± 0.05	0.308 ± 0.006
18	12.00 ± 0.07	0.320 ± 0.006	6.75 ± 0.05	0.286 ± 0.005
19	12.71 ± 0.08	0.308 ± 0.006	6.92 ± 0.05	0.268 ± 0.005
20	13.13 ± 0.08	0.294 ± 0.006	7.38 ± 0.05	0.205 ± 0.004
21	13.51 ± 0.08	0.280 ± 0.006	7.15 ± 0.06	0.239 ± 0.005
22	13.97 ± 0.08	0.256 ± 0.005	7.53 ± 0.05	0.177 ± 0.004
23	14.35 ± 0.09	0.232 ± 0.005	7.68 ± 0.05	0.147 ± 0.003
24	14.43 ± 0.09	0.225 ± 0.005	7.85 ± 0.05	0.109 ± 0.003
25	14.61 ± 0.09	0.213 ± 0.005	7.98 ± 0.05	0.074 ± 0.002

Table 5: Power P and uncertainty for four configurations.

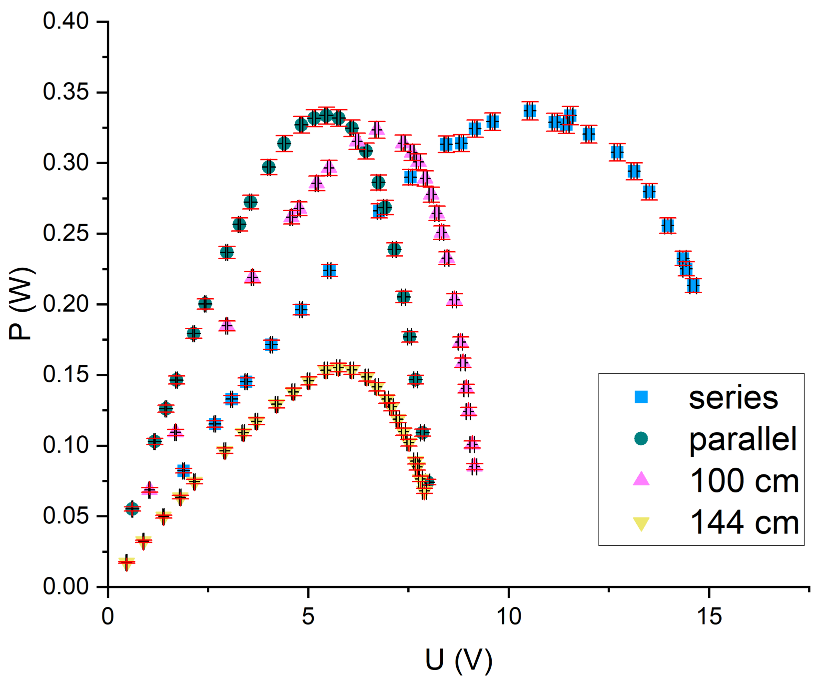

Figure 7: P-V characteristic curves of each configuration.

	100 cm		144 cm	
	$U \pm (0.5\% + 0.01)$ [V]	P [W]	$U \pm (0.5\% + 0.01)$ [V]	P [W]
1	9.15 ± 0.06	0.085 ± 0.002	0.47 ± 0.012	0.0173 ± 0.0005
2	9.09 ± 0.06	0.101 ± 0.002	0.89 ± 0.014	0.0324 ± 0.0008
3	9.00 ± 0.06	0.124 ± 0.003	1.39 ± 0.017	0.0498 ± 0.0011
4	8.94 ± 0.05	0.140 ± 0.003	1.81 ± 0.019	0.0635 ± 0.0013
5	8.86 ± 0.05	0.159 ± 0.003	2.16 ± 0.02	0.075 ± 0.002
6	8.80 ± 0.05	0.173 ± 0.004	2.92 ± 0.02	0.096 ± 0.002
7	8.65 ± 0.05	0.203 ± 0.004	3.38 ± 0.03	0.109 ± 0.002
8	8.46 ± 0.05	0.233 ± 0.005	3.71 ± 0.03	0.117 ± 0.002
9	8.33 ± 0.05	0.251 ± 0.005	4.21 ± 0.03	0.129 ± 0.003
10	8.21 ± 0.05	0.264 ± 0.005	4.63 ± 0.03	0.138 ± 0.003
11	8.07 ± 0.05	0.278 ± 0.005	5.01 ± 0.04	0.146 ± 0.003
12	7.92 ± 0.05	0.289 ± 0.005	5.44 ± 0.04	0.153 ± 0.003
13	7.75 ± 0.05	0.301 ± 0.006	5.75 ± 0.04	0.155 ± 0.003
14	7.59 ± 0.05	0.307 ± 0.006	6.09 ± 0.04	0.153 ± 0.003
15	7.37 ± 0.05	0.314 ± 0.006	6.46 ± 0.04	0.149 ± 0.003
16	6.71 ± 0.04	0.323 ± 0.006	6.71 ± 0.04	0.142 ± 0.003
17	6.22 ± 0.04	0.315 ± 0.006	6.96 ± 0.04	0.133 ± 0.003
18	5.52 ± 0.04	0.296 ± 0.005	7.08 ± 0.05	0.127 ± 0.003
19	5.21 ± 0.04	0.286 ± 0.005	7.24 ± 0.05	0.119 ± 0.003
20	4.77 ± 0.03	0.268 ± 0.005	7.38 ± 0.05	0.110 ± 0.002
21	4.58 ± 0.03	0.262 ± 0.005	7.51 ± 0.05	0.102 ± 0.002
22	3.61 ± 0.03	0.219 ± 0.004	7.68 ± 0.05	0.089 ± 0.002
23	2.97 ± 0.02	0.185 ± 0.003	7.72 ± 0.05	0.085 ± 0.002
24	1.69 ± 0.018	0.109 ± 0.002	7.80 ± 0.05	0.076 ± 0.002
25	1.04 ± 0.015	0.0686 ± 0.0015	7.90 ± 0.05	0.068 ± 0.002

Table 6: Power P and uncertainty for four configurations.

3.3 Other relavant data

For I_{sc} and U_{oc}, we measured the data listing as follows.

	U_{oc} [V]	I_{sc} [mA]
126.0 cm	8.69 ± 0.05	44.3 ± 0.8
95.8 cm	7.71 ± 0.05	46.5 ± 0.8
series	16.42 ± 0.09	45.1 ± 0.8
parallel	8.21 ± 0.05	90.0 ± 1.5

Table 7: Measurement data for U_{oc} and I_{sc}.

Here we will further report other data such as R_{m}, P_{m}, FF, and η.

The resistance of the external load are caluclated through Ohm's law $R = \dfrac{V}{I}$. Take the first set of data as an example,

$$R = \frac{V}{I} = \frac{1.89}{43.5 \times 10^{-3}} = 43.4 \pm 0.9\ \Omega.$$

Perform simialr calculation for each set of data, the results are presented in Table 8

	Series	Parallel	100 cm	144 cm
	R $\pm$ u_R [Ω]			
1	43.4 ± 0.9	6.7 ± 0.2	980 ± 30	12.7 ± 0.4
2	61.8 ± 1.2	13.3 ± 0.3	820 ± 20	24.5 ± 0.6
3	81.9 ± 1.6	16.7 ± 0.3	652 ± 15	38.8 ± 0.8
4	118 ± 2	20.0 ± 0.4	569 ± 13	51.6 ± 1.1
5	172 ± 3	25.5 ± 0.5	495 ± 11	62.6 ± 1.3
6	197 ± 4	29.5 ± 0.5	447 ± 9	88 ± 2
7	227 ± 4	37.3 ± 0.7	368 ± 7	105 ± 2
8	248 ± 5	41.9 ± 0.8	308 ± 6	117 ± 2
9	280 ± 5	46.5 ± 0.8	277 ± 5	137 ± 3
10	329 ± 6	54.4 ± 1.0	255 ± 5	155 ± 3
11	71.9 ± 1.4	61.7 ± 1.1	235 ± 4	172 ± 3
12	97.1 ± 1.8	71.3 ± 1.3	217 ± 4	193 ± 4
13	137 ± 3	80.0 ± 1.4	200 ± 4	213 ± 4
14	259 ± 5	89.1 ± 1.6	187 ± 3	242 ± 5
15	400 ± 8	100.0 ± 1.8	173 ± 3	281 ± 6
16	378 ± 7	114 ± 2	139 ± 3	318 ± 7
17	399 ± 8	134 ± 2	123 ± 2	364 ± 8
18	449 ± 9	159 ± 3	103 ± 2	393 ± 8
19	525 ± 10	178 ± 3	95 ± 2	441 ± 10
20	586 ± 12	265 ± 5	85 ± 2	495 ± 11
21	653 ± 13	214 ± 4	80.2 ± 1.5	552 ± 13
22	763 ± 16	320 ± 6	59.5 ± 1.1	662 ± 16
23	886 ± 19	402 ± 9	47.7 ± 0.9	702 ± 17
24	930 ± 20	565 ± 13	26.1 ± 0.5	796 ± 20
25	1000 ± 20	860 ± 20	15.8 ± 0.3	920 ± 20

Table 8: Resistance R for the four configurations.

Conclude what we have derived so far, the maximum output power and the corresponding $V_\mathrm{m}, I_\mathrm{m}, R_\mathrm{m}$ can be found by consulting Table **??**, Table **??**, and Table 8. The results are presented in Table 9.

	U_m [V]	I_m [mA]	P_m [W]	R_m [Ω]
Series	11.54 ± 0.07	28.9 ± 0.6	0.334 ± 0.006	399 ± 8
Parallel	5.45 ± 0.04	61.2 ± 1.0	0.334 ± 0.006	89.1 ± 1.6
100.0 cm	6.71 ± 0.04	48.2 ± 0.8	0.323 ± 0.006	139 ± 3
144.0 cm	5.75 ± 0.04	29.1 ± 0.5	0.155 ± 0.003	213 ± 4

Table 9: V_m, I_m and P_m in four configurations.

The fill factor FF can be then calculated out of Eq.1. Take the 100.0 cm configuration as an example, (here we assume 100.0 cm shares the same data with 95.8 cm due to data missing)

$$FF = \frac{P_\mathrm{m}}{U_\mathrm{oc} I_\mathrm{sc}} = \frac{0.334}{7.71 \times 46.5 \times 10^{-3}} = 0.932 \pm 0.019.$$

The fill factor of each single configuration are calculated as shown and the results are presented in Table 10.

	FF
144.0 cm	0.403 ± 0.011
100.0 cm	0.932 ± 0.019

Table 10: Fill factor of single configuration.

The measurement data for the area are shown in Table 2. See this table at the beginning of this section. The measurement result of power of six points on the board are shown in Table 11.

	1	2	3	4	5	6
$P_{100.0}$ [W/m^2] $\pm$ 10 [W/m^2]	391	275	168	381	250	207
$P_{144.0}$ [W/m^2] $\pm$ 10 [W/m^2]	169	108	112	161	110	111
$P_{126.0}$ [W/m^2] $\pm$ 10 [W/m^2]	207	139	136	210	135	142
$P_{95.8}$ [W/m^2] $\pm$ 10 [W/m^2]	203	192.5	174.3	163.0	159.2	243

Table 11: Measurement data for solar power.

The average of the power per square meter is

$$\overline{P_{100.0}} = \frac{1}{6}(391 + 275 + 168 + 381 + 250 + 207) = (300 \pm 100)\ \mathrm{W/m^2},$$

$$\overline{P_{144.0}} = \frac{1}{6}(169 + 108 + 112 + 161 + 110 + 111) = (130 \pm 30)\ \mathrm{W/m^2}.$$

The total power is

$$P_{\mathrm{in},100.0} = \overline{P_{100.0}} L_1 L_2 = 300 \times 0.2610 \times 0.2100 = 16 \pm 11\ \mathrm{W},$$

$$P_{\mathrm{in},144.0} = \overline{P_{144.0}} L_1 L_2 = 130 \times 0.2610 \times 0.2100 = 7 \pm 5\ \mathrm{W}.$$

The power energy conversion efficiency can then be calculated from Eq.(2), as

$$\eta_{100.0} = \frac{P_\mathrm{m}}{P_{\mathrm{in},100.0}} \times 100\% = \frac{0.323}{16} \times 100\% = 2.0\% \pm 1.4\%,$$

$$\eta_{144.0} = \frac{P_\mathrm{m}}{P_{\mathrm{in},144.0}} \times 100\% = \frac{0.155}{7} \times 100\% = 2.2\% \pm 1.6\%,$$

4 Uncertainty Analysis

4.1 $I - V$ Characteristics

The uncertainty of V is $0.5\% + 0.01$ V, and the uncertainty of I is $1.5\% + 0.1$ mA. Take the first set of data as an example,

$$u_V = 0.5\% \times 1.89 + 0.01 = 0.02\,\mathrm{V}.$$

$$u_I = 1.5\% \times 43.5 + 0.1 = 0.8\,\mathrm{mA}.$$

All the uncertainties of V and I are calculated in this way and the results are shown in Table 12.

	Series		Parallel		100 cm		144 cm	
	u_V [V]	u_I [mA]	u_V [V]	u_I [mA]	u_V [V]	u_I [mA]	u_V [V]	u_I [mA]
1	0.02	0.8	0.013	1.5	0.06	0.2	0.012	0.7
2	0.03	0.8	0.016	1.5	0.06	0.3	0.014	0.6
3	0.03	0.8	0.018	1.4	0.06	0.3	0.017	0.6
4	0.04	0.8	0.019	1.4	0.05	0.3	0.019	0.6
5	0.05	0.7	0.02	1.4	0.05	0.4	0.02	0.6
6	0.05	0.7	0.03	1.4	0.05	0.4	0.02	0.6
7	0.06	0.7	0.03	1.3	0.05	0.5	0.03	0.6
8	0.06	0.7	0.03	1.3	0.05	0.5	0.03	0.6
9	0.06	0.7	0.03	1.3	0.05	0.6	0.03	0.6
10	0.07	0.6	0.03	1.2	0.05	0.6	0.03	0.5
11	0.03	0.8	0.03	1.2	0.05	0.6	0.04	0.5
12	0.03	0.8	0.04	1.2	0.05	0.6	0.04	0.5
13	0.04	0.7	0.04	1.1	0.05	0.7	0.04	0.5
14	0.06	0.7	0.04	1.0	0.05	0.7	0.04	0.5
15	0.07	0.6	0.04	1.0	0.05	0.7	0.04	0.4
16	0.07	0.6	0.04	0.9	0.04	0.8	0.04	0.4
17	0.07	0.6	0.05	0.9	0.04	0.9	0.04	0.4
18	0.07	0.5	0.05	0.8	0.04	0.9	0.05	0.4
19	0.08	0.5	0.05	0.7	0.04	0.9	0.05	0.3
20	0.08	0.5	0.05	0.6	0.03	0.9	0.05	0.3
21	0.08	0.5	0.06	0.6	0.03	1.0	0.05	0.3
22	0.08	0.4	0.05	0.5	0.03	1.0	0.05	0.3
23	0.09	0.4	0.05	0.4	0.02	1.0	0.05	0.3
24	0.09	0.4	0.05	0.3	0.018	1.1	0.05	0.2
25	0.09	0.4	0.05	0.3	0.015	1.1	0.05	0.2

Table 12: Uncertainty of the data for I-V characteristic.

4.2 $P - V$ Characteristics

For $P = VI$, its uncertainty is calculated as

$$u_P = \sqrt{(\frac{\partial P}{\partial V}u_V)^2 + (\frac{\partial P}{\partial I}u_I)^2} = \sqrt{(Iu_V)^2 + (Vu_I)^2}.$$

Take the first set of data as an example,

$$u_P = \sqrt{(Iu_V)^2 + (Vu_I)^2} = \sqrt{(43.5 \times 10^{-3} \times 0.02)^2 + (1.89 \times 0.8 \times 10^{-3})^2} = 0.002\,\mathrm{W}.$$

	Series u_P [W]	Parallel u_P [W]	100 cm u_P [W]	144 cm u_P [W]
1	0.002	0.0015	0.002	0.0005
2	0.002	0.002	0.002	0.0008
3	0.003	0.003	0.003	0.0011
4	0.004	0.003	0.003	0.0013
5	0.005	0.003	0.003	0.002
6	0.005	0.004	0.004	0.002
7	0.006	0.004	0.004	0.002
8	0.006	0.005	0.005	0.002
9	0.006	0.005	0.005	0.003
10	0.006	0.005	0.005	0.003
11	0.003	0.006	0.005	0.003
12	0.003	0.006	0.005	0.003
13	0.004	0.006	0.006	0.003
14	0.006	0.006	0.006	0.003
15	0.006	0.006	0.006	0.003
16	0.006	0.006	0.006	0.003
17	0.006	0.006	0.006	0.003
18	0.006	0.005	0.005	0.003
19	0.006	0.005	0.005	0.003
20	0.006	0.004	0.005	0.002
21	0.006	0.005	0.005	0.002
22	0.005	0.004	0.004	0.002
23	0.005	0.003	0.003	0.002
24	0.005	0.003	0.002	0.002
25	0.005	0.002	0.0015	0.002

Table 13: Uncertainty of data for P.

4.3 Other relevant data

4.3.1 R

For $R = \frac{V}{I}$, its uncertainty is calculated as

$$u_R = \sqrt{(\frac{\partial R}{\partial V}u_V)^2 + (\frac{\partial R}{\partial I}u_I)^2} = \sqrt{(\frac{u_V}{I})^2 + (-\frac{V}{I^2}u_I)^2}.$$

Take the first set of data as an example,

$$u_R = \sqrt{(\frac{u_U}{I})^2 + (-\frac{U}{I^2}u_I)^2} = \sqrt{(\frac{0.02}{43.5 \times 10^{-3}})^2 + (-\frac{1.89}{43.5^2} \times 0.8)^2} = 0.9\,\Omega.$$

Perform simialr calculation for each set of data, the results are presented in Table 14

	Series	Parallel	100 cm	144 cm
		u_R [Ω]		
1	0.9	0.2	30	0.4
2	1.2	0.3	20	0.6
3	1.6	0.3	15	0.8
4	2	0.4	13	1.1
5	3	0.5	11	1.3
6	4	0.5	9	2
7	4	0.7	7	2
8	5	0.8	6	2
9	5	0.8	5	3
10	6	1.0	5	3
11	1.4	1.1	4	3
12	1.8	1.3	4	4
13	3	1.4	4	4
14	5	1.6	3	5
15	8	1.8	3	6
16	7	2	3	7
17	8	2	2	8
18	9	3	2	8
19	10	3	2	10
20	12	5	2	11
21	13	4	1.5	13
22	16	6	1.1	16
23	19	9	0.9	17
24	20	13	0.5	20
25	20	20	0.3	20

Table 14: Uncertainty of data for R.

4.3.2 U_{oc}, I_{sc}, and P_{m}

The uncertainty of V_{oc} and I_{sc} is calulated in the same way as U and I. The results are displayed in Table **??**, together with the uncertainty of the maximum power. Notice that since we have no data for P_{m} in 126.0 cm or 95.8 cm, we may as well just use the maximual uncertainty of power of 100 cm and 144 cm for references.

	$u_{U_{\text{oc}}}$ [V]	$u_{I_{\text{sc}}}$ [mA]	$u_{P_{\text{m}}}$ [W]
126.0 cm	0.05	0.8	0.003
95.8 cm	0.05	0.8	0.006

Table 15: Uncertainty of V_{oc}, I_{sc}, and P_{m}.

4.3.3 Fill Factor

The uncertainty of fill factor, $FF = P_{\text{m}}/(V_{\text{oc}}I_{\text{sc}})$, is calculated as

$$\begin{aligned} u_{FF} &= \sqrt{(\frac{\partial FF}{\partial P_{\text{m}}}u_{P_{\text{m}}})^2 + (\frac{\partial FF}{\partial U_{\text{oc}}}u_{U_{\text{oc}}})^2 + (\frac{\partial FF}{\partial I_{\text{sc}}}u_{I_{\text{sc}}})^2} \\ &= \sqrt{(\frac{1}{U_{\text{oc}}I_{\text{sc}}}u_{P_{\text{m}}})^2 + (-\frac{P_{\text{m}}}{U_{\text{oc}}^2 I_{\text{sc}}}u_{U_{\text{oc}}})^2 + (-\frac{P_{\text{m}}}{U_{\text{oc}}I_{\text{sc}}^2}u_{I_{\text{sc}}})^2}, \end{aligned}$$

Take the first set of data as an example,

$$\begin{aligned} u_{FF} &= \sqrt{(\frac{1}{U_{\text{oc}}I_{\text{sc}}}u_{P_{\text{m}}})^2 + (-\frac{P_{\text{m}}}{U_{\text{oc}}^2 I_{\text{sc}}}u_{U_{\text{oc}}})^2 + (-\frac{P_{\text{m}}}{U_{\text{oc}}I_{\text{sc}}^2}u_{I_{\text{sc}}})^2} \\ &= \sqrt{(\frac{1}{8.69 \times 44.3 \times 10^{-3}} \times 0.003)^2 + (-\frac{0.155}{8.69^2 \times 44.3 \times 10^{-3}} \times 0.05)^2 + (-\frac{0.155}{8.69 \times (44.3 \times 10^{-3})^2} \times 0.0008)^2} \\ &= 0.011. \end{aligned}$$

The uncertainties are calculated as shown above and the results are shown in Table 16.

	u_{FF}
126.0 cm	0.011
95.8 cm	0.019

Table 16: Uncertainty of FF.

4.3.4 Energy Conversion Efficiency

The type–B uncertainty of power measurement is $u_P = \Delta_{P,B} = \Delta_{dev} = 10$ [W/m^2]. Since the power measurement is repeated for 6 times, the type–A uncertainty needs to be considered.

In this case, $n = 6$, $t_{0.95} = 2.57$[4], the type–A uncertainty is

$$\begin{aligned}\Delta_{P,A} &= \frac{t_{0.95}}{\sqrt{n}} s_{\overline{P}} \\ &= \frac{t_{0.95}}{\sqrt{n}} \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(P_i - \overline{P})^2} \\ &= \frac{2.57}{\sqrt{6}} \sqrt{\frac{1}{6-1}\sum_{i=1}^{6}(P_i - \overline{P})^2}.\end{aligned}$$

The total uncertainty is then

$$u_{\overline{P}} = \sqrt{\Delta_{P,A}^2 + \Delta_{P,B}^2} = \sqrt{\left(\frac{2.57}{\sqrt{6}} \sqrt{\frac{1}{6-1}\sum_{i=1}^{6}(P_i - \overline{P})^2}\right)^2 + 10^2}.$$

Hence, for the two single configurations,

$$u_{\overline{P_{100.0}}} = \sqrt{\left(\frac{2.57}{\sqrt{6}} \sqrt{\frac{1}{6-1}\sum_{i=1}^{6}(P_i - 278.7)^2}\right)^2 + 10^2} = 100 \text{ W/m}^2,$$

$$u_{\overline{P_{144.0}}} = \sqrt{\left(\frac{2.57}{\sqrt{6}} \sqrt{\frac{1}{6-1}\sum_{i=1}^{6}(P_i - 128.5)^2}\right)^2 + 10^2} = 30 \text{ W/m}^2,$$

The uncertainty of $P_{\text{in}} = \overline{P} L_1 L_2$ is calculated as

$$\begin{aligned}u_{P_{\text{in}}} &= \sqrt{(\frac{\partial P_{\text{in}}}{\partial \overline{P}} u_{\overline{P}})^2 + (\frac{\partial P_{\text{in}}}{\partial L_1} u_{L_1})^2 + (\frac{\partial P_{\text{in}}}{\partial L_2} u_{L_2})^2} \\ &= \sqrt{(L_1 L_2 u_{\overline{P}})^2 + (\overline{P} L_2 u_{L_1})^2 + (\overline{P} L_1 u_{L_2})^2}.\end{aligned}$$

Hence, substituting the values, it can be obtained that

$$u_{P_{\text{in},100.0}} = 11 \text{ W}, \qquad u_{P_{\text{in},144.0}} = 5 \text{ W}.$$

Finally, the uncertainty of $\eta = (P_{\text{m}}/P_{\text{in}}) \times 100\%$ can be calculated, as

$$\begin{aligned}u_\eta &= \sqrt{(\frac{\partial \eta}{\partial P_{\text{m}}} u_{P_{\text{m}}})^2 + (\frac{\partial \eta}{\partial P_{\text{in}}} u_{P_{\text{in}}})^2} \times 100\% \\ &= \sqrt{(\frac{1}{P_{\text{in}}} u_{P_{\text{m}}})^2 + (-\frac{P_{\text{m}}}{P_{\text{in}}^2} u_{P_{\text{in}}})^2} \times 100\%.\end{aligned}$$

Substituting the values, it is derived in the end that

$$u_{\eta_{100.0}} = 1.4\,\%, \qquad u_{\eta_{144.0}} = 1.6\,\%.$$

5 Conclusion and Discussion

5.1 Conclusion

In this exercise, we recorded the current voltage $I - V$ data for solar cells and then studied the $I - V$ characteristics. Besides, we also derived some other characteristics based on $I - V$ characteristics, such as

$P-V$ characteristics and even $P-R$ characteristics, which is not drawn though. The data we derived is listed below. (Table 17)

	Series	Parallel	100.0 cm	144.0 cm
U_{m} [V]	11.54 ± 0.07	5.45 ± 0.04	6.71 ± 0.04	5.75 ± 0.04
I_{m} [mA]	28.9 ± 0.6	61.2 ± 1.0	48.2 ± 0.8	29.1 ± 0.5
P_{m} [W]	0.334 ± 0.006	0.334 ± 0.006	0.323 ± 0.006	0.155 ± 0.003
R_{m} [Ω]	399 ± 8	89.1 ± 1.6	139 ± 3	213 ± 4
FF	/	/	0.932 ± 0.019	0.403 ± 0.011
η	/	/	$2.0\% \pm 1.4\%$	$2.2\% \pm 1.6\%$

Table 17: Results.

where some conclusions can be derived:

- I decreases as the V increases, as Fig.(6) shows.
- As U increases, the power first increases and then decreases. The output power attains its maximum at some $R = R_m$, which agrees with the theoretical conclusions derived from the Ohm's laws. (Fig.(7))
- As for V_{m} and V_{oc}, the series is twice larger than the single and the parallel is equal to the single while as for I_{m} and I_{sc}, the series is equal to the single and the parallel is twice larger than the single. (Table 17)

Detailed analysis and discussion about experimental results are left to DISCUSSION part.

5.2 Discussion

Here we will discuss the problems in this exercise, some potential errors which may lead to huge variation, and some suggestions.

5.2.1 Problems

- **Temperature[5]:** We observed that I_{sc} and U_{oc} were instable for a certain period of time, especially at the initial time when light exerted. This phenomenon brings out two unexpected but awful consequences: 1. Measured data is less confidential due to this variation; 2. the maximum output power (P_m) corresponding to the best load and the fill factor (FF) value may decrease.
- **Leakage:** The solar panel has some leak on it due to thousands of times usage.At the point of leak, the resistance suddenly increases, which leads to more Joule heat. The Joule heat distributes on the panel unevenly, which causes the panel more like several distinct parts rather than a whole, complete board. This fact may accumulate the effect of temperature mentioned above.
- **Light angle:** When we adjusted the angle of incident light, some photons may crash into others' solar panel, which affects others' experiments a lot.

5.2.2 Potential errors

- Different temperarture may cause data variation.
- Unevenly distributed heat may lessen the magnitude of P_m and FF.
- Other searchlights may have a huge effect on our own experiments.

5.2.3 Imporvements

- Increase the power of fans beside the solar panel.
- Add a hood between each groups to decrease the light from other groups.
- Apply more advanced experimental device, which can adjust the incident angle more flexible and precise[6].
- Replace the traditional solar panel with new material solar panels, such as GaAs[7].

6 Reference

[1] M. Krzyzosiak (2021). Exercise 3 - lab manual [rev 5]. (UMJI-SJTU, Shanghai).
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APPENDIX - DATA SHEET